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Characterization of the Discharge From an Ablating-Capillary Arc Ignition System Equipped With a Poly(Ethylene Terephthalate) Liner

by Michael J. McQuaid

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Abstract

Under an experimental program to study plasma-propellant interactions, tests were conducted in which an ablating-capillary arc ignition system, normally equipped with a poly(ethylene) (PE) liner, was equipped with a poly(ethylene terephthalate) (PET) liner. This report summarizes the results of numerical simulations performed to compare the properties of the arc discharge generated from these two liner materials. The simulations indicate that, for a given current in the range from 5,000 to 15,000 A, the load impedances produced by the plasmas formed from the decomposition of PE and PET are nearly the same. Thus, from the standpoint of the (electrical) discharge of the pulse-forming network, the PET liner appears the same as the PE liner. However, the physical and chemical properties of the plasmas derived from PE and PET are quite different. In particular, the simulations indicate that the plasmas produced by the decomposition of PET are denser and will exit with lower velocity than plasmas formed from the decomposition of PE.

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1. Introduction

Ablating-capillary arcs are a means of converting electrical energy into a form suitable for the ignition of propulsion charges in large-caliber gun systems [1]. In ignition systems that utilize this approach, electrical energy stored in a pulse-forming network (PFN) is initially discharged via a thin metallic wire strung through the capillary. The initial discharge explodes the wire, "instantaneously" producing an ionized (plasma) gas into which the PFN continues to dump energy. Ablation of material from the capillary wall, which is generally attributed to (and modeled as) a radiation driven process [2], serves to sustain the arc by replenishing gas that exits the capillary. The overall process produces a "dense" (10^{23}–10^{26} m^{-3}), "low-temperature" (10,000–30,000 K) plasma whose composition is primarily derived from decomposed capillary material [2]. This fluid subsequently flows into the propellant bed and ignites it (directly).

This report summarizes an attempt to understand the nature of differences in the discharge from an ablating capillary arc when the capillary material is changed from poly(ethylene) [PE, $(C_2H_4)_n$] to poly(ethylene terephthalate) [PET, $(C_{10}H_8O_4)_n$]. The study was prompted by questions that arose during an experimental test program designed to identify and characterize plasma-propellant interactions relevant to electrothermal-chemical (ETC) ignition [3]. In this program, propellant grains in a "closed bomb" are ignited by the discharge from an ablating-capillary arc, and the grains then extinguished by rapid depressurization. To determine the influence of plasma-propellant interactions, a variety of experimental techniques are employed to analyze the partially burned grains [3]. (These analyses are in addition to the traditional burn rate reduction that is performed.) During the course of this study, the system was operated with capillaries lined with several different materials. This series of tests was undertaken to determine if the performance of the system could be improved with respect to that achieved with a "standard" PE liner. (It was thought, for example, that by using a liner that produced oxygen or halogen atoms, the ignition process might be enhanced.) In addition, the repeatability of the performance of the PFN was also an issue. Of the materials that were tested to address the latter concern, Mylar—a member of the PET polymer family—yielded the most promising results.

Bases for differences in the performance of the system when it is equipped with a PET liner are not, however, apparent from the diagnostics employed in the experiments. For example, one possibility for observed differences may be that the plasmas derived from PET have a different electrical conductivity than plasmas derived from PE. If so, a different load impedance would result. Given that the load impedance can affect the efficiency of electrical energy conversion [2], it is an important consideration in the interpretation of the experimental results. However, the experimental measurements do not provide this information (directly). (To acquire this information, the actual voltage drop across the capillary needs to be measured, and such a measurement is a difficult undertaking.)

In an attempt to identify differences in system operation that are produced by changing from a PE to a PET liner, Powell and Zielinski's (PZ) code for simulating ablating-capillary arc dynamics was employed to estimate system parameters that are not experimentally measured. Model results indicate that the plasmas produced from these materials behave similarly from the standpoint of the PFN (electrical) discharge. However, for the same input power, the plasmas derived from a PET capillary will be much denser and exit with lower velocity than the plasmas derived from a PE capillary. The implications of these differences with respect to the performance of the ignition system are discussed.

2. Model Considerations

The model developed by Powell and Zielinski for the characterization of ablating-capillary arc dynamics has been described in detail elsewhere [2]. Briefly, it is a one-dimensional, steady-state model that assumes current is conducted through a plasma in the interior of a dielectric cylinder. Ohmic heating produces high temperatures, and radiation from the plasma ablates material from the capillary wall, replenishing gas that exits the capillary. The program solves a set of conservation equations that describe the flow-ablation process. Assumptions underlying the development of the system of equations are that the fluid achieves local thermodynamic equilibrium and that the ideal gas law applies. The Saha equation, employed with a reaction product set limited to monatomic species, is utilized to compute chemical

compositions [2]. For the simulations performed in this study, the material data input file developed by PZ for PE was employed [2]. Details of the PET data developed for this study are provided in the Appendix.

The input parameters for the model simulations were chosen based on consideration of the geometry and operating conditions of the experimental system employed by Del Güercio [3]. In this system, the capillary is nominally 8-cm long and has a inner diameter of 0.32 cm. Simulations were run assuming that the current rises linearly (with respect to time) from 5,000 to 15,000 A over a 1-ms interval. This case was chosen based on (1) covering the range of current values over which the experimental system is operated and (2) previous experience that shows that model results are relatively insensitive to the discharge history (see, for example, Powell and Zielinski [2]). That is, plasma properties are found to depend almost exclusively on the instantaneous value of the current. Thus, the results at a given current are expected to be representative of a case in which the experimental system is operated in an "ideal" manner at that current (i.e., the current and voltage pulses of the PFN electrical discharge resemble square waves at that current).

3. Results and Discussion

Figures 1–7 compare model results obtained for various physical properties of the plasmas generated by ablating PET and PE. Figure 1 compares the temperatures of the plasmas vs. current. In both cases, the temperature rises from about 16,500 K at 5,000 A to about 24,000 K at 15,000 A. These temperatures are in a range where the model is expected to yield reasonable results [4]. Given the differences in the properties of the liner materials, the similarity of the temperatures over the current range is somewhat surprising.

Perhaps an even more surprising result is the similarity of the electrical conductivities of the plasmas produced from these materials over this current range (see Figure 2). It was expected that PET's relatively high concentration of (atomic) carbon (with its low ionization potential) and its relatively low atomization energy would lead to the production of a more highly conductive plasma. The results shown indicate that the load will not depend on whether

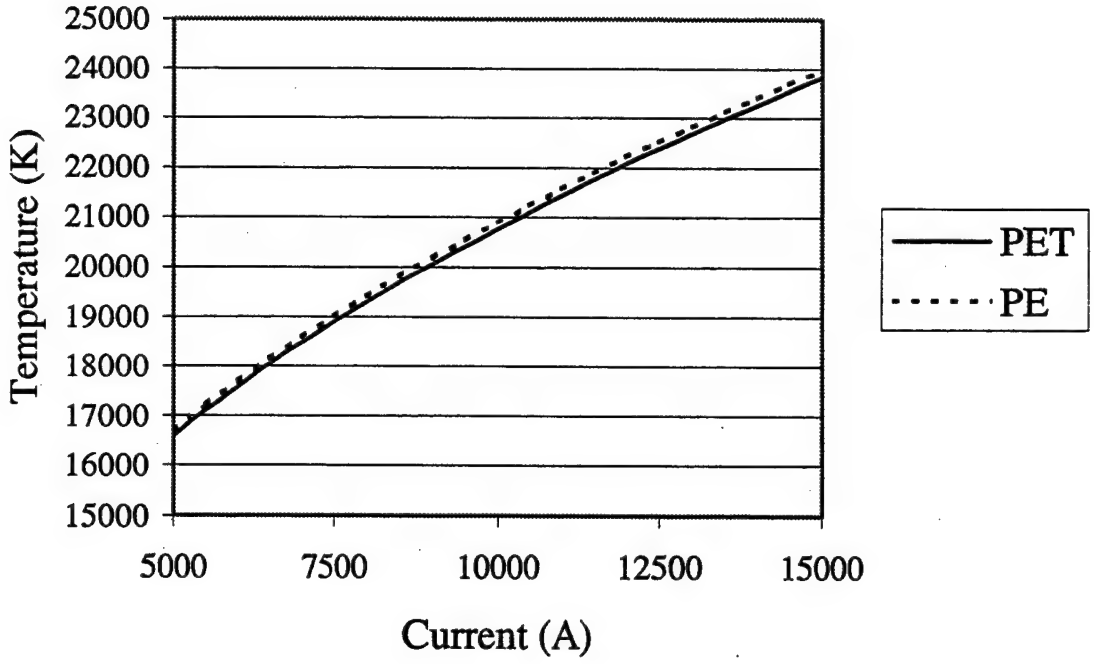

Figure 1. Plasma Temperature vs. Current for PET and PE Liners.

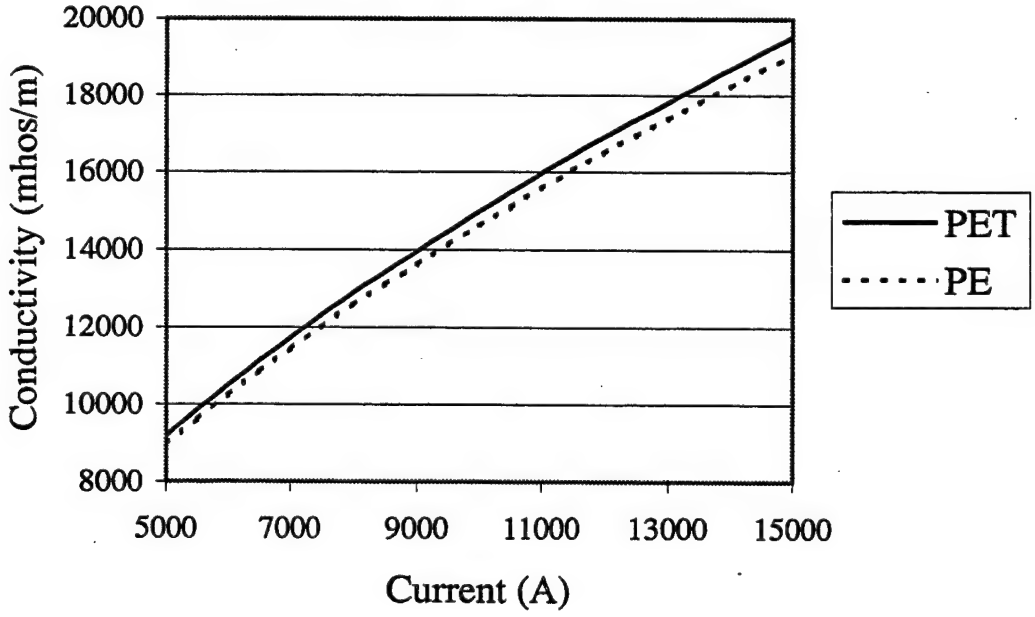

Figure 2. Plasma Conductivity vs. Current for PET and PE Liners.

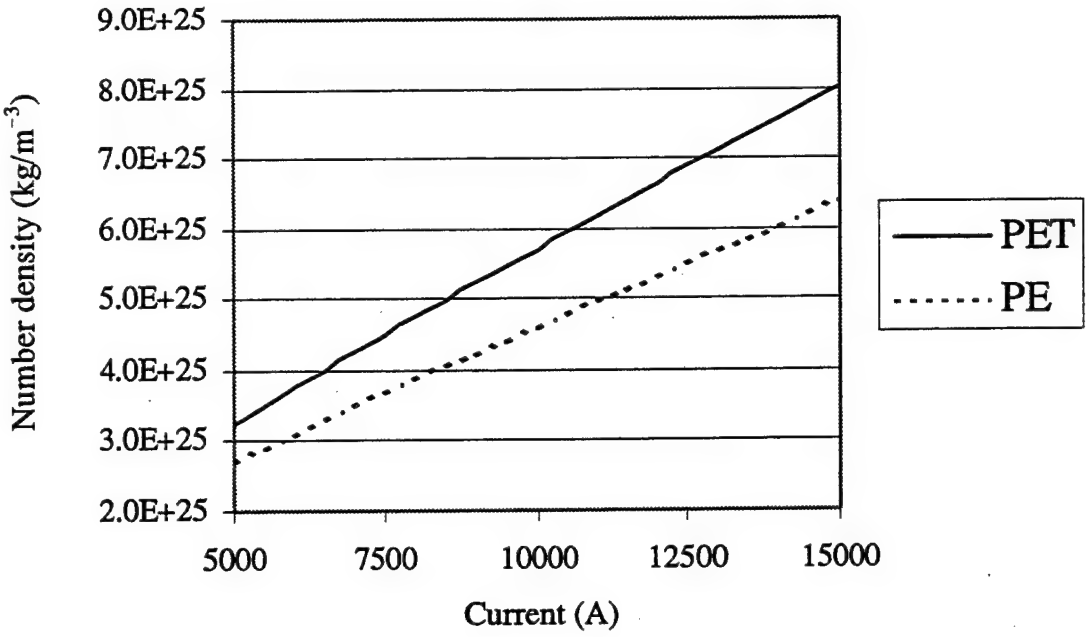

Figure 3. Plasma Number Density vs. Current for PET and PE Liners.

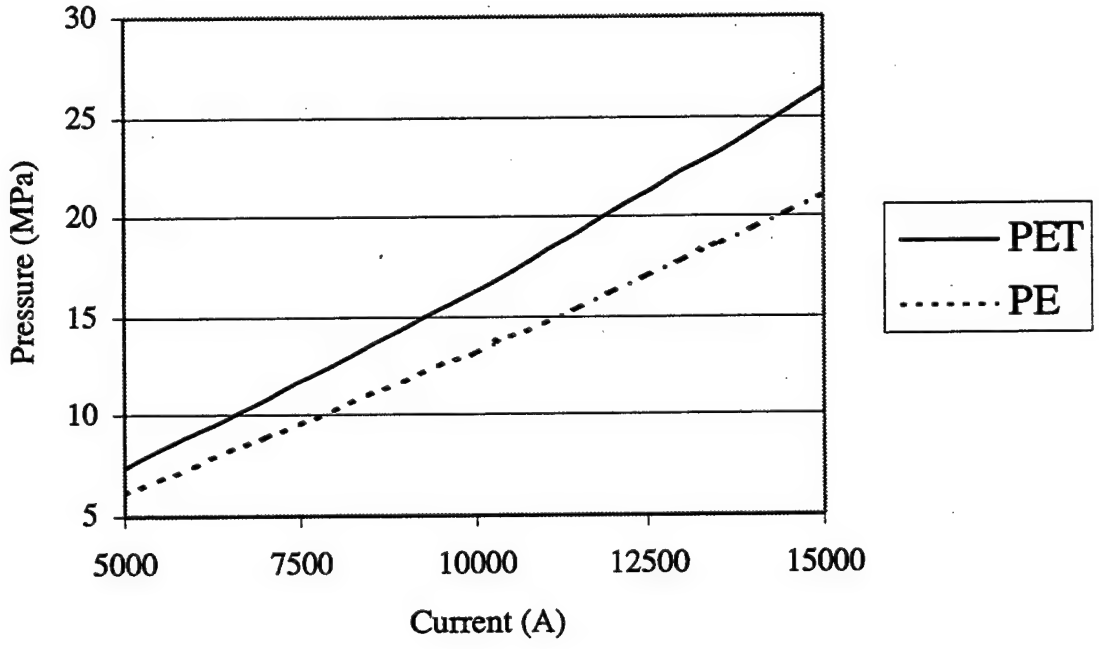

Figure 4. Plasma Pressure vs. Current for PET and PE Liners.

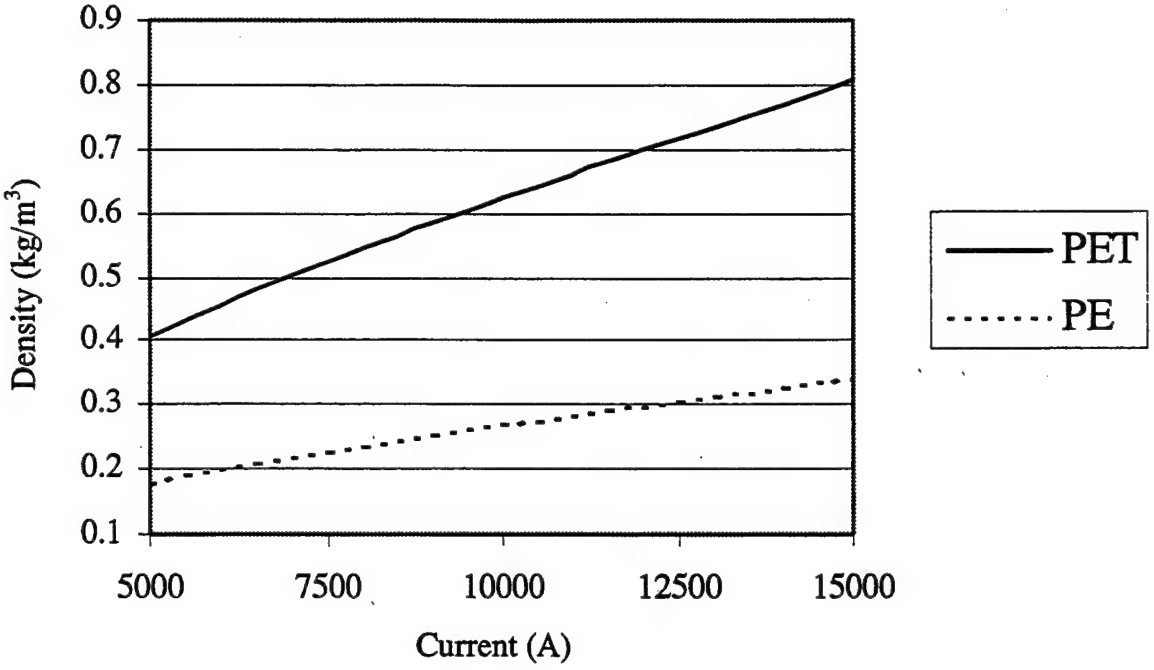

Figure 5. Plasma Density vs. Current for PET and PE Liners.

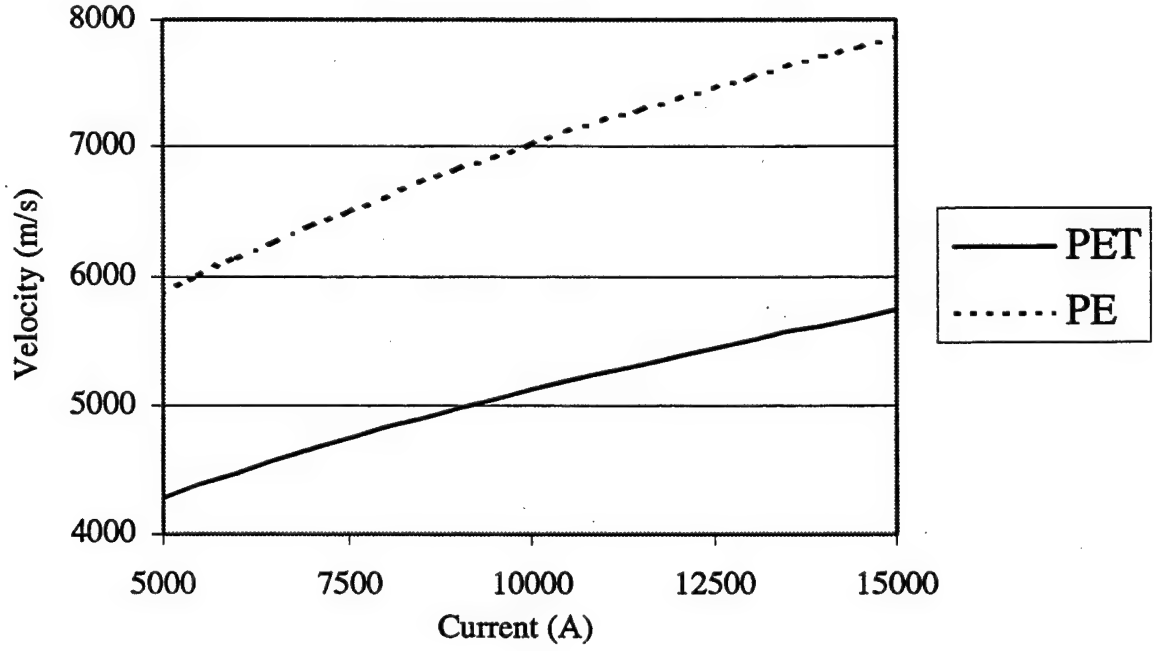

Figure 6. Plasma Velocity vs. Current for PET and PE Liners.

PET or PE is employed for the liner. And, since the efficiency with which the PFN couples energy into the plasma is a function of the load impedance, it can be assumed that experimental differences due to coupling efficiency are unimportant.

Figure 3 compares the total particle number densities produced by the system at the capillary exit. Given that the power dissipated in the two liners is the same and that the heat of atomization of PE (383 kJ/mole-atoms) is lower than that of PET (491 kJ/mole-atoms), it is surprising that the PE liner produces lower number-density plasmas. The result occurs because of the high degree of ionization of carbon relative to hydrogen at the same temperature.

Figure 4 compares the pressures generated by the system at the capillary exit. As in the case of total particle number densities (Figure 3), the lower values of pressure in the PE-equipped system reflect the fact that the system produces plasmas of about the same temperature with either liner but the number densities of the plasmas derived from PE are lower.

Figure 5 compares the (mass) densities generated by the system at the capillary exit. The much higher densities observed with PET reflect the higher average molecular weight of the PET stoichiometry. However, it should be cautioned that the average molecular weight will depend on the degree to which the atoms are ionized. Carbon has a lower ionization potential than hydrogen, and its concentration in PET is high relative to that of PE. Thus, its ionization will offset considerations based on stoichiometry alone.

Figure 6 compares the exit velocities for the discharge from the system. The exit velocities of the PE-equipped system is approximately 50% higher than that of the PET-equipped system for the same current. The higher values for the PE-equipped system were expected based on consideration of the high relative concentration of hydrogen in PE.

Figure 7 compares the particle fluxes at the capillary exit for the two cases, the particle fluxes for the PE-equipped case being about 10% higher than the PET-equipped case. This suggests that the pressurization rate achieved with PET-based plasma will be somewhat lower than that

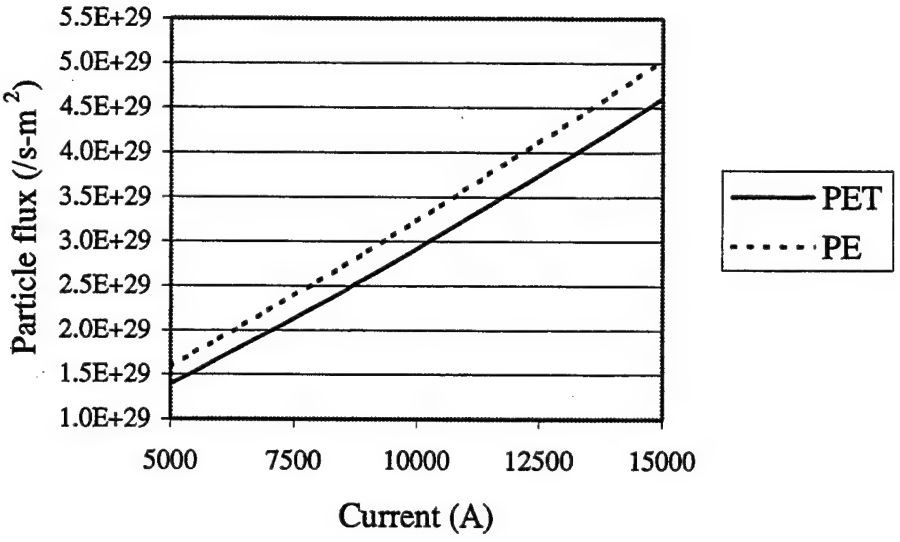

Figure 7. Plasma Particle Flux vs. Current for PET and PE Liner Materials.

achieved with a PE-based plasma. Of course, the dynamics of the plasma as it expands into the combustion chamber will depend on its interaction with the fluid in the chamber, and it is risky to extrapolate the results presented above to explain the nature of some of the experimental results. To better address such issues, simulations of the rest of the process should be performed [5].

Finally, a question arose as to whether the (thin) PET liner might be completely consumed prior to the completion of the electrical discharge. At 15,000 A, the highest current level considered in this study, the model calculates a surface recession rate of 0.064 m/s. Thus, for a 1-ms duration electrical pulse, the surface will regress about 0.06 mm (2.4 mil). Given that the PET liners employed in the experimental system were at least 0.12 mm (5 mil) thick, it seems unlikely that they would be completely consumed during an experiment.

4. Summary

Simulations of the dynamics of an ablating-capillary arc ignition system were performed to characterize differences in the system produced by changing from a PE to a PET-lined capillary. The simulations show that the plasmas formed from PE and PET will produce the same load

impedance for the same current and, thus, that similar electrical energy conversion efficiencies will be realized. The temperature of the effluent from the system also did not depend on which liner was employed. In other respects, the plasmas produced are significantly different. When PET is employed, much denser plasmas are produced, and they exit with much lower velocities than plasmas derived from PE.

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5. References

1. Katulka, G. L., and J. Dyvik. "Experimental Results of Electrical Plasma Ignition in 120-mm Solid Propellant Tank Gun Firings." *Proceedings of the 33rd JANNAF Combustion Subcommittee Meeting*, CPIA Publication 653, vol. 3, pp. 103–110, 1996.

2. Powell, J. D., and A. E. Zielinski. "Theory and Experiment for an Ablating-Capillary Discharge and Application to Electrothermal-Chemical Guns." BRL-TR-3355, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1992.

3. Del Güercio, M. "Electrothermal-Chemical (ETC) Closed Chamber Characterization of Plasma Capillaries." *Proceedings of the 36th JANNAF Combustion Subcommittee Meeting*, 1999.

4. McQuaid, M. J., and M. J. Nusca. "Calculating the Chemical Compositions of an Ablating Capillary Arc Ignition System." ARL-TR-2043, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 1999.

5. Nusca, M. J., and M. J. McQuaid. "Modeling the Open-Air Plasma Jet From an ETC Igniter Using a Multi-Species Reacting Flow CFD Code." To appear in *Proceedings of the 36th JANNAF Combustion Subcommittee Meeting*, 1999.

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Appendix:

Physical Property Data for Poly(Ethylene Terephthalate)

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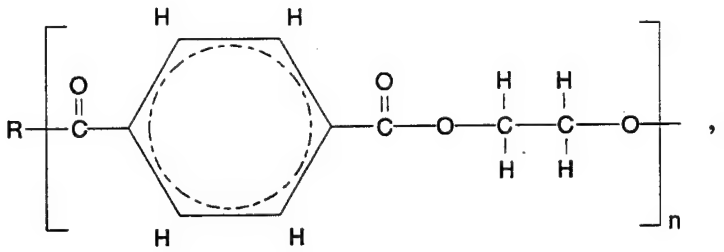
The model of ablating-capillary arc dynamics developed by Powell and Zielinski (PZ) requires knowledge of the stoichiometry, density, and "heat of atomization" of the material from which the capillary is composed.[1] Knowledge of the energy level structure and collision cross sections of constituent atoms is also needed. This appendix presents the establishment of these data (as built from a literature search) for a class of materials referred to as poly(ethylene terephthalate) (PET). Mylar belongs to this class of materials.

The structure of PET is



with the stoichiometry of the monomer being $C_{10}H_8O_4$.[2] The end group (R-) for Mylar is CH_3O. The average value of n will depend on the specific material used, but it is assumed large enough that the monomer stoichiometry can be used for the polymer as a whole. The density of this material is reported[2] to fall in the range from 1.38 to 1.40 gr/cm^{-3}, and a value of 1.39 gr/cm^{-3} was employed for the calculations presented in this report.

Other parameters of the solid material that are required by the code are referred to by Powell and Zielinski as the "heat of vaporization" and the "heat of dissociation." These "designations" are somewhat misleading, and here are combined and referred to as a "heat of atomization"—i.e., the value that establishes how much energy is required to completely atomize a given quantity of (solid) material. This definition/interpretation is consistent with the parameter(s)

[1] Powell, J. D., and A. E. Zielinski. "Theory and Experiment for an Ablating-Capillary Discharge and Application to Electrothermal-Chemical Guns." BRL-TR-3355, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1992.

[2] Brandup, J., and E. H. Immergut (eds.) *Polymers Handbook.* New York: J. Wiley & Sons, 1975.

employed in the energy balance of the PZ model, and more clearly reflects the way the parameter is calculated.

The heat of atomization can be calculated from a two-step process. The first step is the production of the polymer elements in their standard states—i.e., the heat of formation:

$$C_{10}H_8O_4 \rightarrow 10C(\text{graphite}) + 4H_2 + 2O_2.$$

The energy required for this step (4.8 kJ/g) can be calculated from the heat of combustion of the material (-21.6 kJ/g).[2] The second step is the production of atoms from the standard state elements

$$10C(\text{graphite}) + 4H_2 + 2O_2 \rightarrow 10C + 8H + 4O.$$

The energy required for this step (51.5 kJ/g) was calculated based on the heat of formation data for C, H, and O listed in the NIST/JANNAF thermochemical tables.[3] Thus, the total heat of atomization for PET is approximately 56 kJ/g. For comparison, the heat of atomization of PE is 82 kJ/g.[1]

The energy level structure of the atoms composing the solid material are needed for partition function calculations performed to establish the chemical compositions in the plasma. Powell and Zielinski describe these considerations for monoatomic carbon and hydrogen species,[1] and the values they employed, which were obtained from the reference by Moore,[4] are used in the current study. For O, O^+, and O^{++}, Moore's tables[4] provided the required information, with the levels listed in Tables A1–A3 employed in the calculations.

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[3] Chase, M. W. (ed.) *NIST*-JANAF *Thermochemical Tables.* 4th edition, *Journal of Physical and Chemical Reference Data*, Monograph no. 9, New York: American Institute of Physics, 1998.

[4] Moore, C. E. "Atomic Energy Levels as Derived From the Analyses of Optical Spectra. vol. I, ^{1}H to ^{23}V." NBS-NSRDS 35 National Bureau of Standards, Washington, DC, 1948.

For the collision cross sections of neutral atoms with electrons, which are needed for the computation of a plasma's electrical conductivity, the values employed by PZ for C ($30\pi a^2$) and H ($17\pi a^2$) were used in this study. It appears that these values were obtained from the reference by Massey and Burhop.[5] The value for the collision cross section of O used in this study ($8\pi a^2$) was also obtained from this reference (which reported the work of Sunshine, Aubrey, and Bederson).[6]

Table A-1. O I Energy Levels[4]

Designation	g	E (cm^{-1})
$2p^4\ ^3P$	5	0.0
$2p^4\ ^3P$	3	158.5
$2p^4\ ^3P$	1	226.5
$2p^4\ ^1D$	5	15868
$2p^4\ ^1S$	1	33792
$3s\ ^5S$	5	73768
$3s\ ^3S$	3	76795
$3p\ ^5P$	3,5,7	86630
$3p\ ^3P$	5,3,1	88630
$4s\ ^5S$	5	95476
$4s\ ^3S$	3	96230

Table A-2. O II Energy Levels[4]

Designation	g	E (cm^{-1})
$2p^3\ ^4S^o$	4	0.0
$2p^3\ ^2D$	6	26808
$2p^3\ ^2D$	4	26829
$2p^3\ ^2P$	4	40467
$2p^3\ ^2P$	2	40468

[5] Massey, H. S. W., and E. H. S. Burhop. *Electronic and Ionic Impact Phenomena.* London: Oxford University Press, 1969.

[6] Sunshine, G., B. B. Aubrey, and B. Bederson. *Physical Review*, vol. 154, p. 1, 1967.

Table A-3. O III Energy Levels[4]

Designation	g	E (cm^{-1})
$2p^2\ ^4P$	1	0.0
$2p^2\ ^4P$	3	113.4
$2p^2\ ^4P$	5	306.8
$2p^2\ ^1D$	5	20271
$2p^3\ ^1S$	1	43184
$2p^3\ ^5S$	5	60312

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